Wavefront Sensing with a Coupled Cavity for Torsion-Bar Antenna

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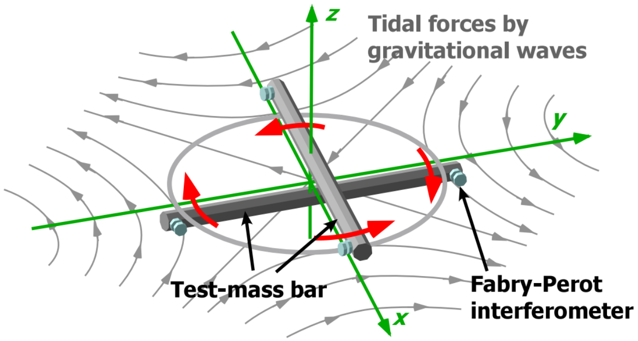
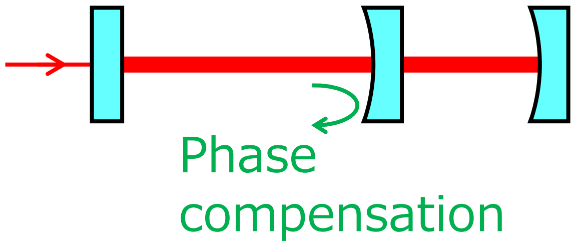
Overview

- Developing
  TOrsion-Bar Antenna (TOBA)
  to detect GW in low freq.

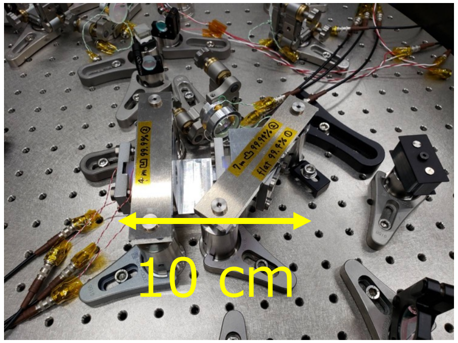


M. Andoho+, PRL 105, 161101 (2010)

- Proposed an improved WaveFront Sensor with a Coupled cavity (Coupled WFS) as an angular sensor for TOBA
  - Angular signal is amplified
  - Beam jitter noise is small

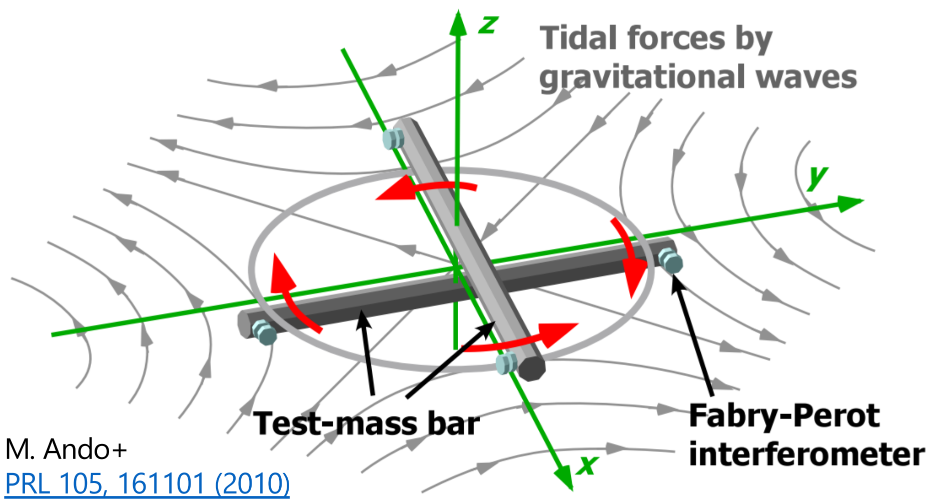


- Demonstrated Coupled WFS
  - Established control method
  - Evaluated signal amplification

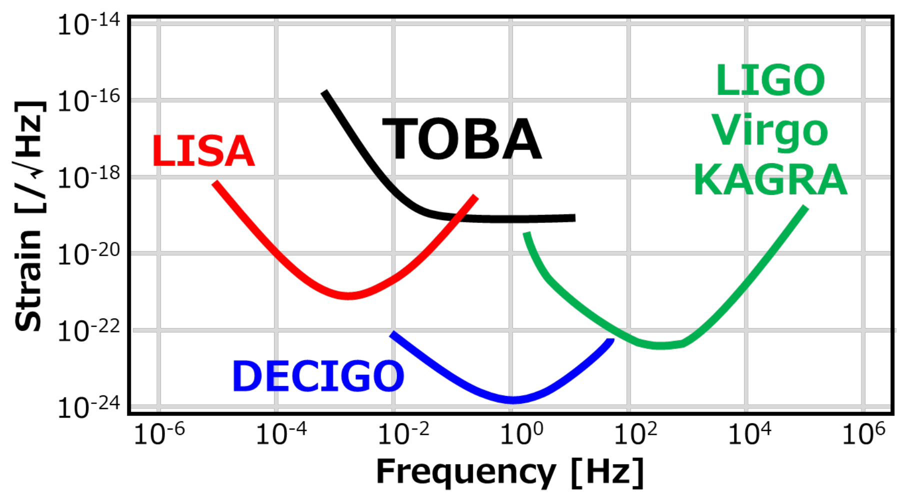


TOBA: TOrsion-Bar Antenna

- Ground-based GW detector for low freq.
  - Final target: 10^{-19} /√Hz at 0.1 Hz
- Aim to detect the torsional rotation of test masses suspended horizontally
- The resonant frequency of torsional motion is low
  → Good sensitivity in low freq. even on the ground
  - Inexpensive
  - Easy to maintain
  - Science on the ground



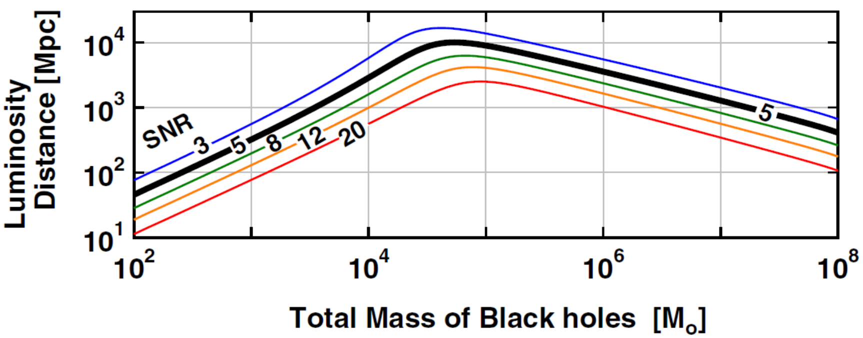
M. Ando+
PRL 105, 161101 (2010)



Science of TOBA

Astrophysics

- Intermediate mass BH binary merger
  - Within ~1 Mpc (Phase-III)
  - Within ~10 Gpc (Final)

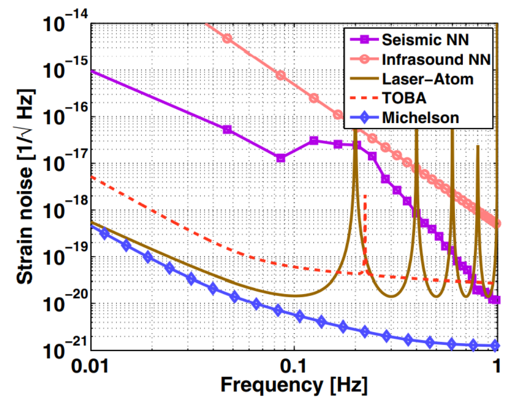


M. Ando+, PRL 105, 161101 (2010)

- GW stochastic background
  - Ω_{GW} ~10^{-7} (Final)

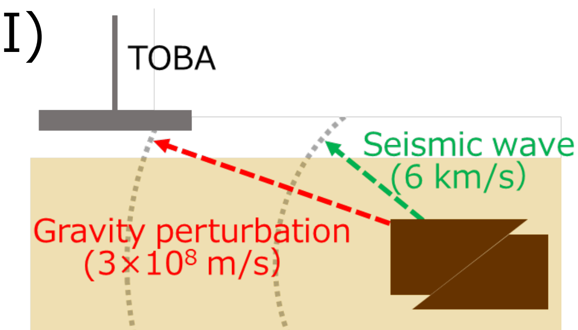
Geophysics

- Newtonian noise
  - First direct detection



J. Harms+
PRD 88, 122003 (2013)

- Earthquake early warning
  - M7 earthquake at a distance of 100 km within 10 sec (Phase-III)

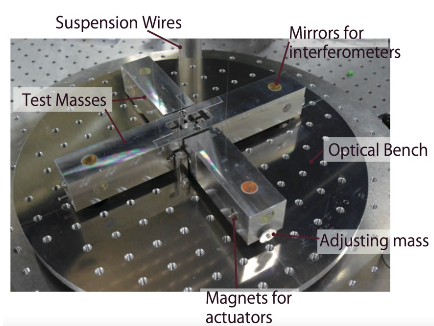


Development roadmap of TOBA

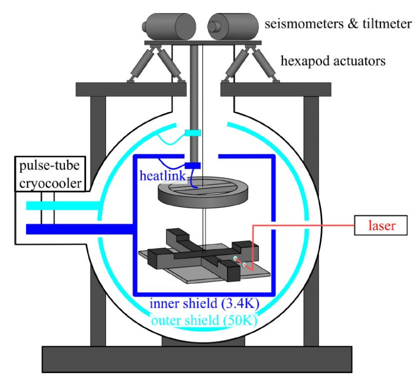
Now

Phase-I	Phase-II	Phase-III	Final

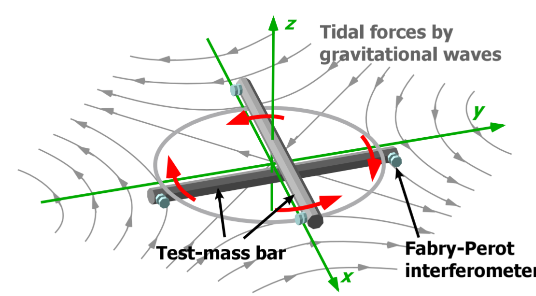
Phase-I / Phase-II	Phase-III	Final
Principle test	Technical demonstration	GW observation
10^{-8} /√Hz (Established)	10^{-15} /√Hz (Target)	10^{-19} /√Hz (Target)
~20 cm bars	35 cm bars	10 m bars
Room temp.	Cryo. Temp. (4 K)	Cryo. Temp. (4 K)



K. Ishidoshiro+, PRL 106, 161101 (2011)
A. Shoda+, PRD 95, 082004 (2017)



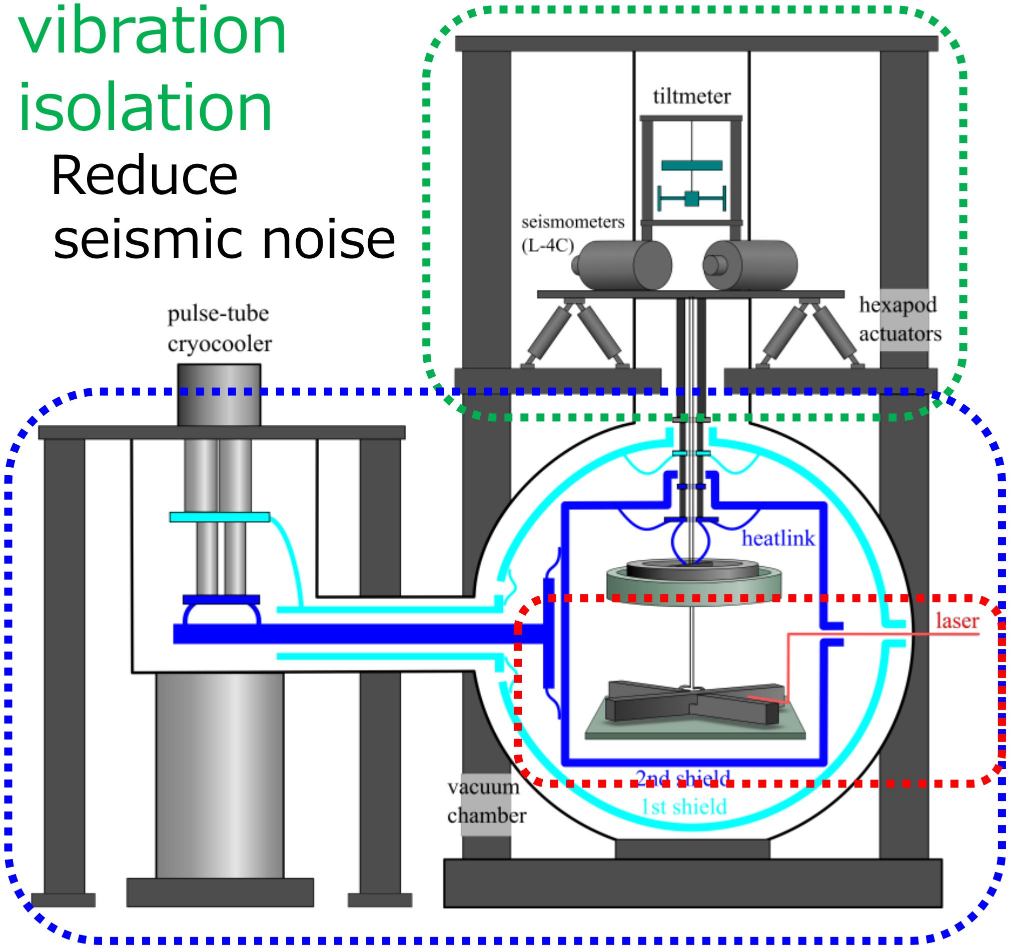
T. Shimoda+, Int. J. Mod. Phys. D 29, 1940003 (2020)

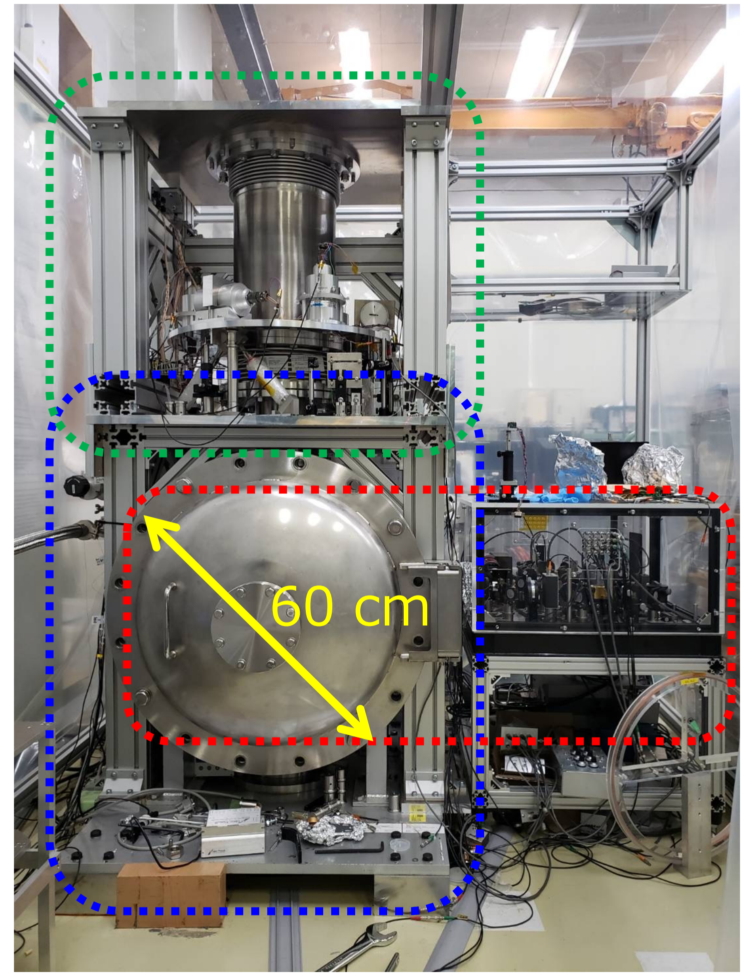


Configuration of Phase-III TOBA

T. Shimoda, Ph.D. thesis (2019)

Active vibration isolation
Reduce seismic noise

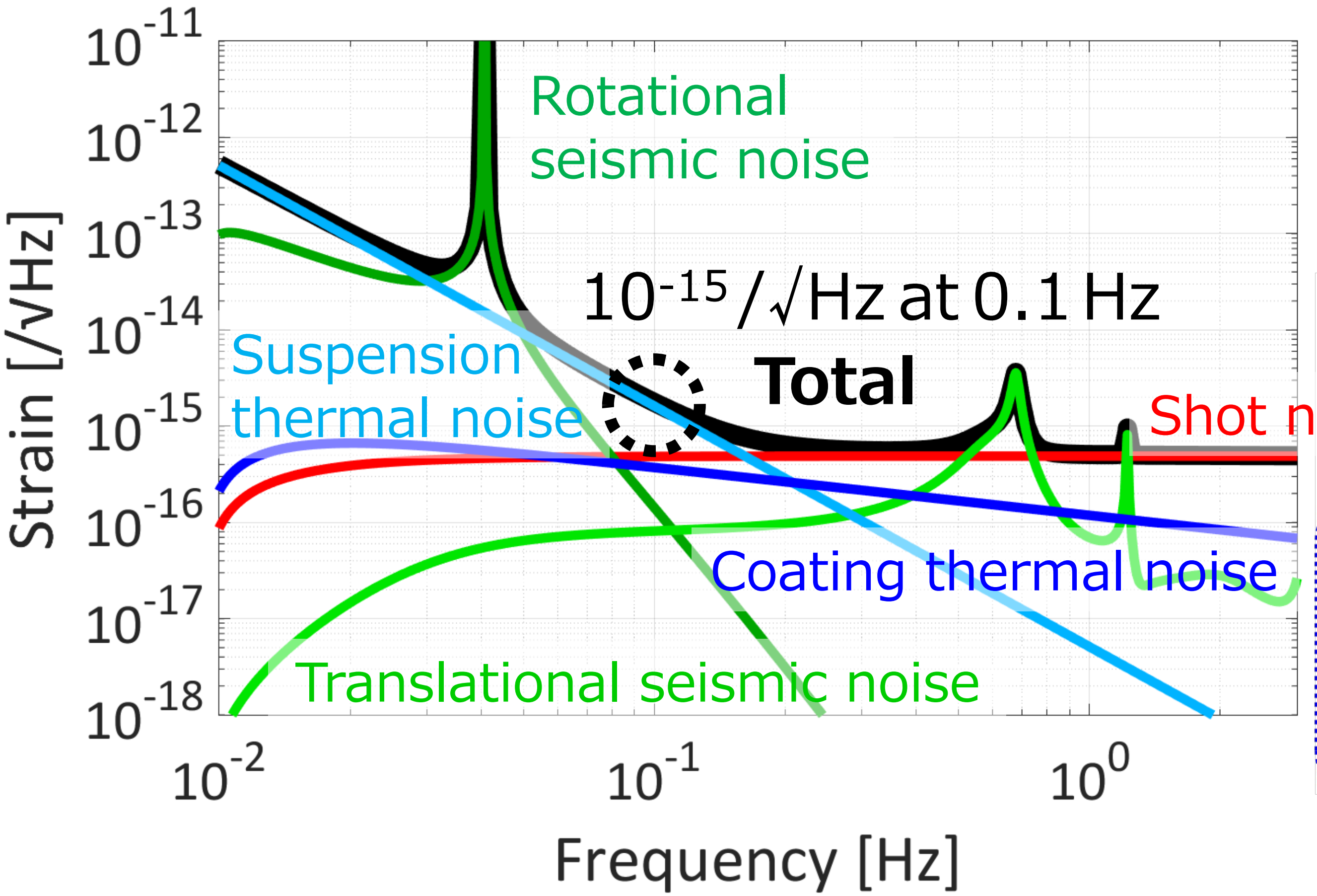


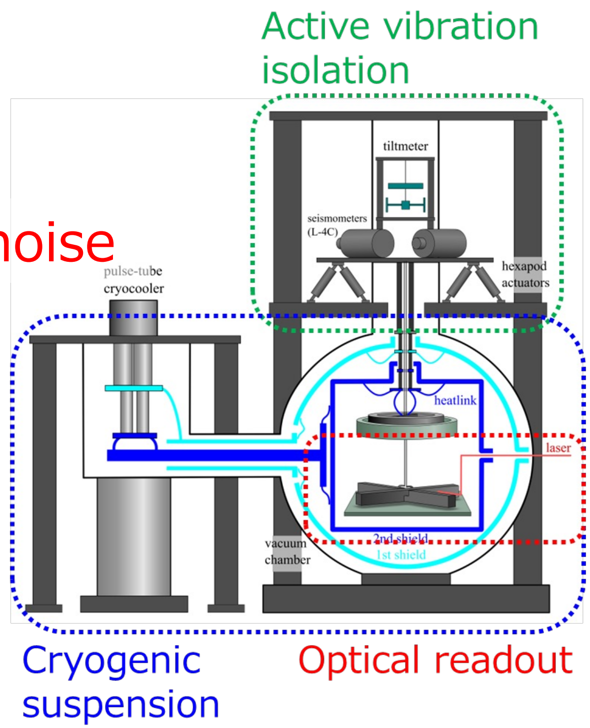


Cryogenic suspension
Torsion pendulums at 4 K

Optical readout
Detect the rotation of the pendulums

Design sensitivity of Phase-III TOBA

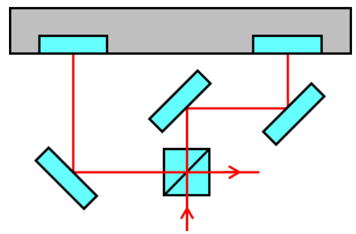
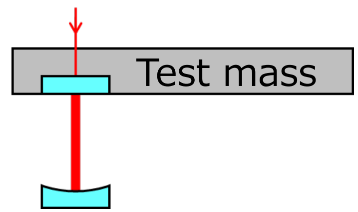
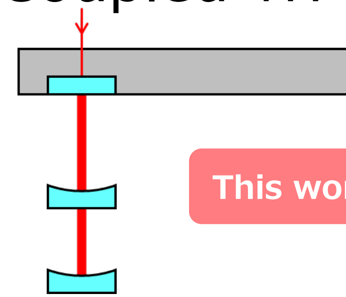




- Our group is developing elements
  - Suspension wire with high Q-value at 4 K
  - Cryogenic monolithic optics
  - Wavefront sensor with a coupled cavity (Coupled WFS)

Comparison of angular sensors

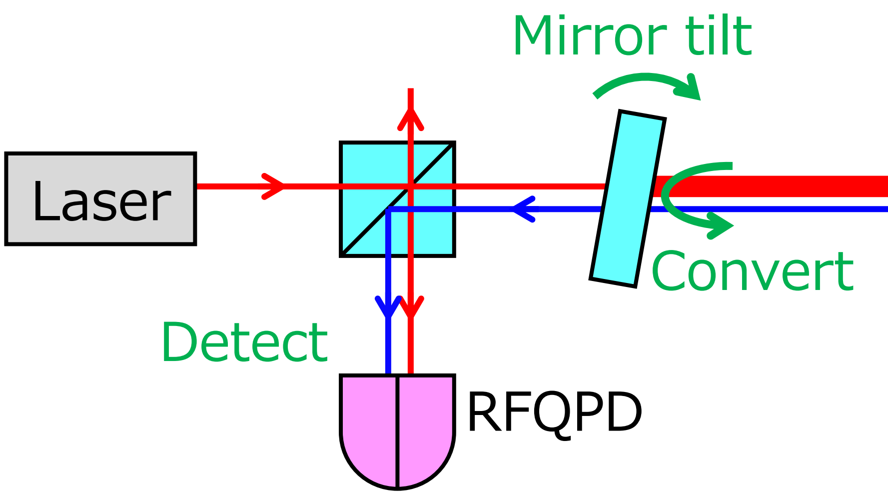
- Need a sensitive angular sensor
  to detect the rotation of torsion pendulums

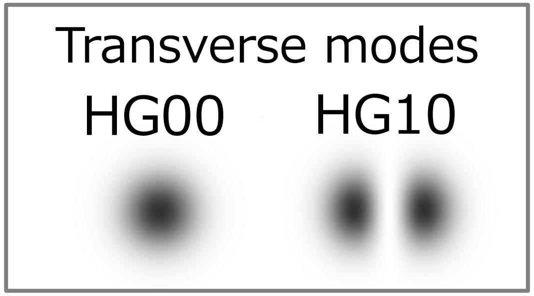
	Michelson interferometer	Wavefront sensor	Coupled WFS
			 **This work**
Shot noise Requirement: 5×10^{-16} rad/$\sqrt{\text{Hz}}$		 No signal amplification	 Signal amplification
Freq. noise	 Non-parallel of two mirrors		
Beam jitter	 Asymmetry of two light paths		 No amplification of beam jitter
Thermal noise		 Narrow range measurement	 Narrow range measurement
Linear range			 Trade-off with signal amplification

Wavefront sensor

- WaveFront Sensor (WFS):
  angular sensor with an optical cavity

- HG10 is generated by mirror tilt
- Detect interference between HG00 and HG10
- Take the difference between left and right signals



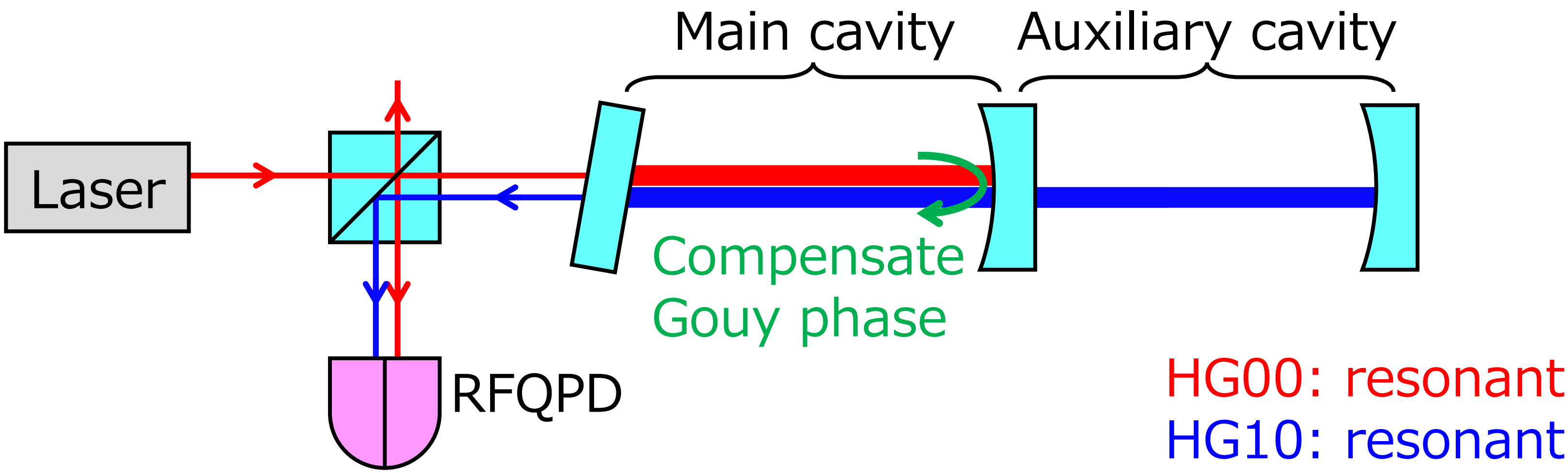


- HG00 and HG10 do not resonate simultaneously due to Gouy phase

  → HG10 is not amplified in the cavity

Coupled wavefront sensor

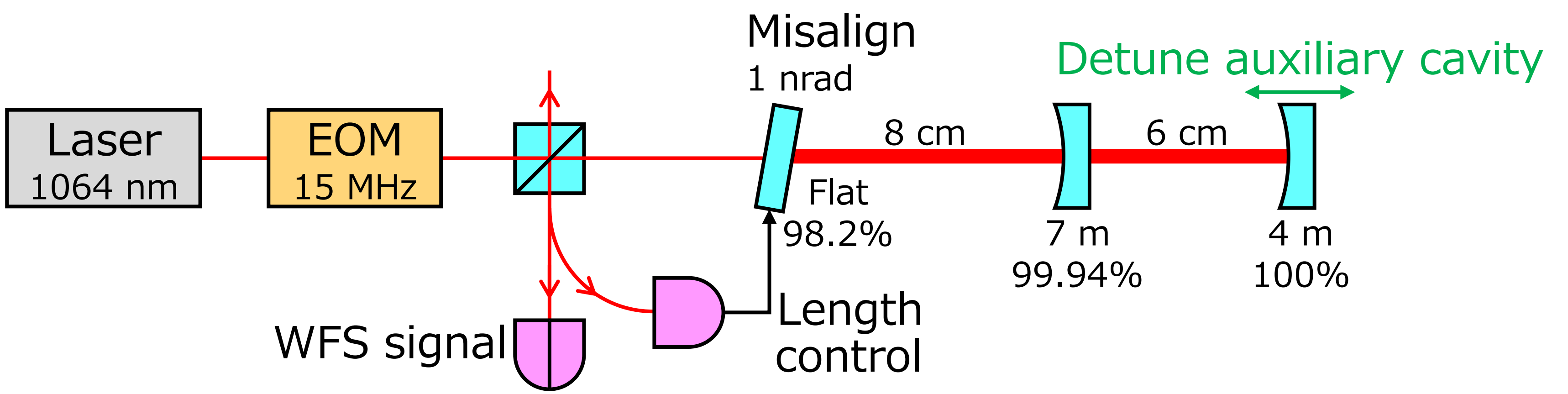
- Coupled wavefront sensor (Coupled WFS):
  wavefront sensor with a coupled cavity



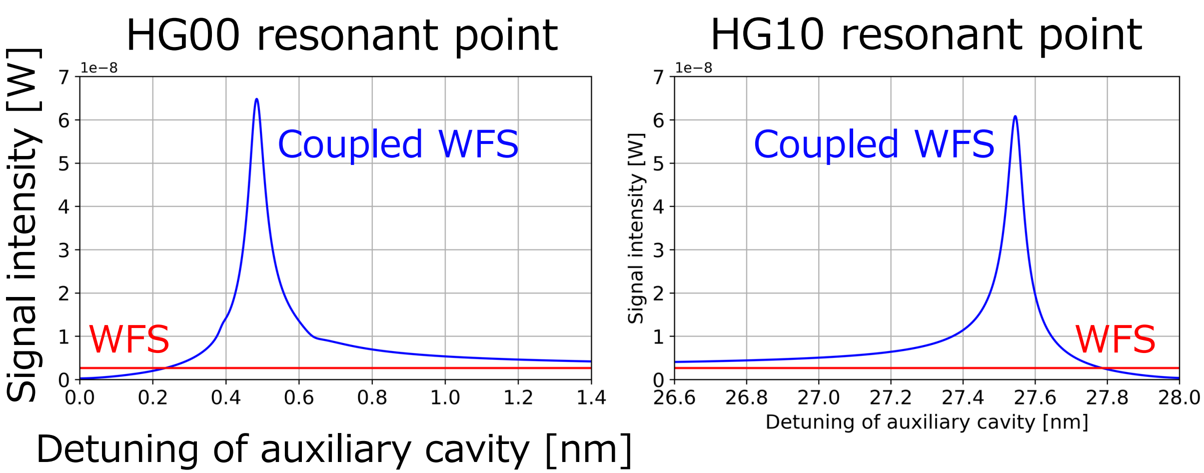
- HG00 and HG10 can resonate simultaneously due to Gouy phase compensation by the auxiliary cavity
  → HG10 is amplified in the main cavity
  → Coupled WFS signal is larger than WFS signal
- Beam jitter is not amplified in the main cavity
  → Better S/N ratio to beam jitter noise

Simulation for Coupled WFS

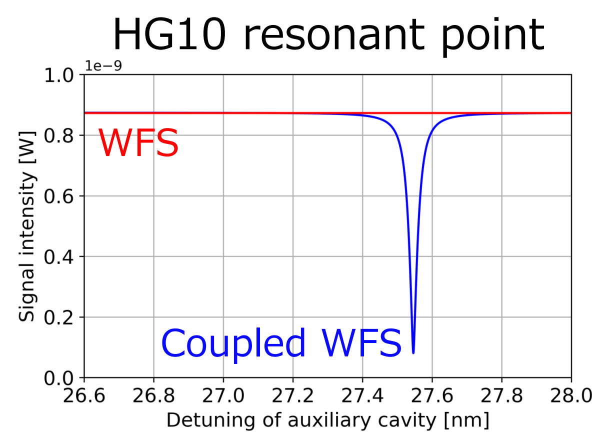
- Complicated configuration of Coupled WFS
  → Calculation with simulation software FINESSE



- Signal amplification around resonant points of HG00 and HG10



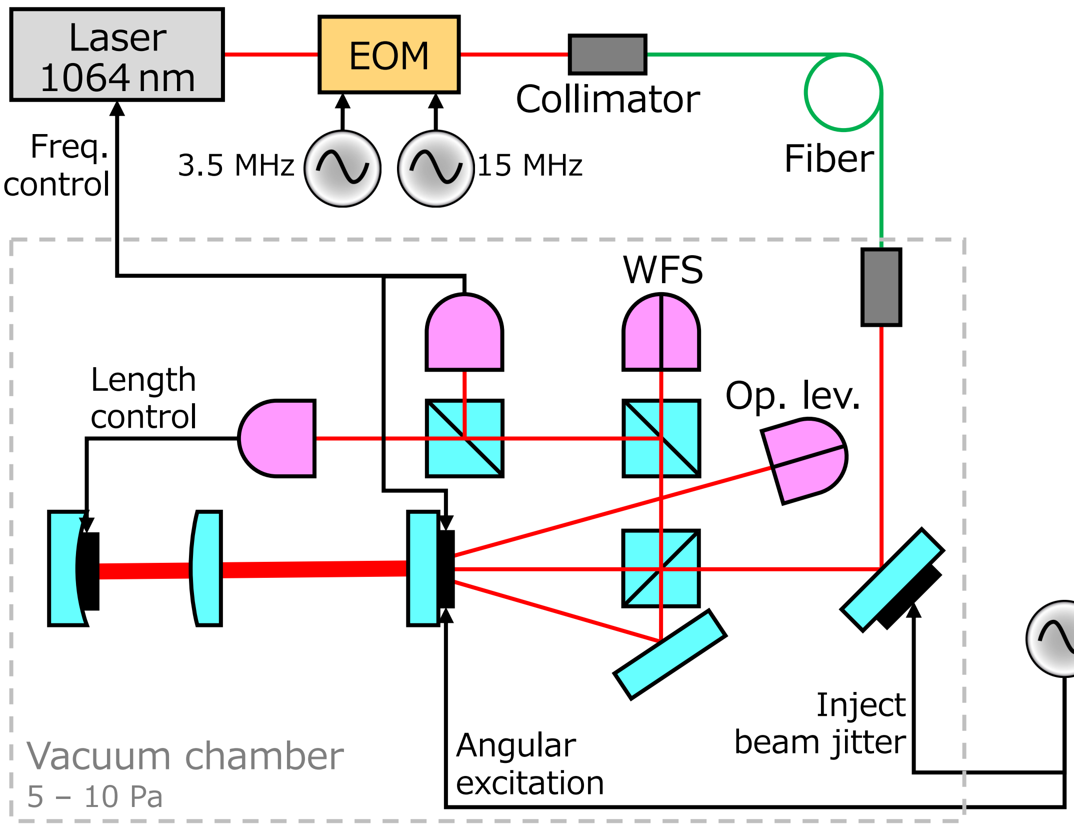
- No amplification to beam jitter noise

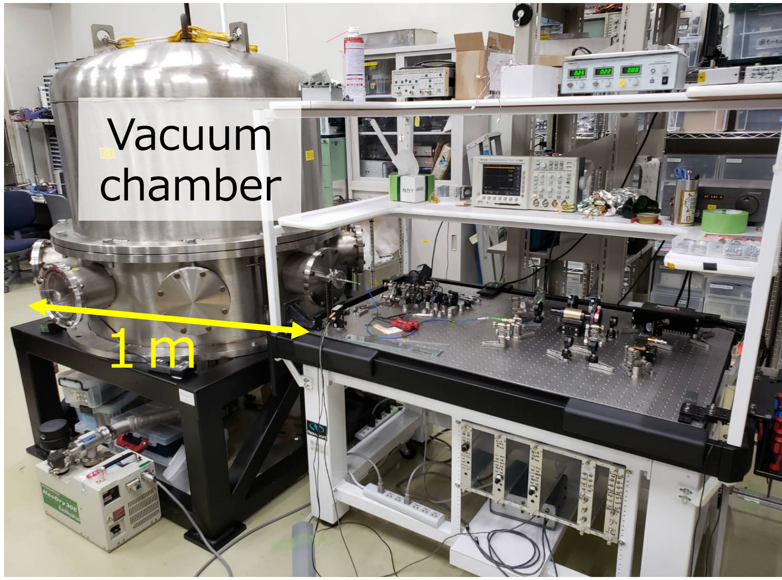


Experimental demonstration

Goal

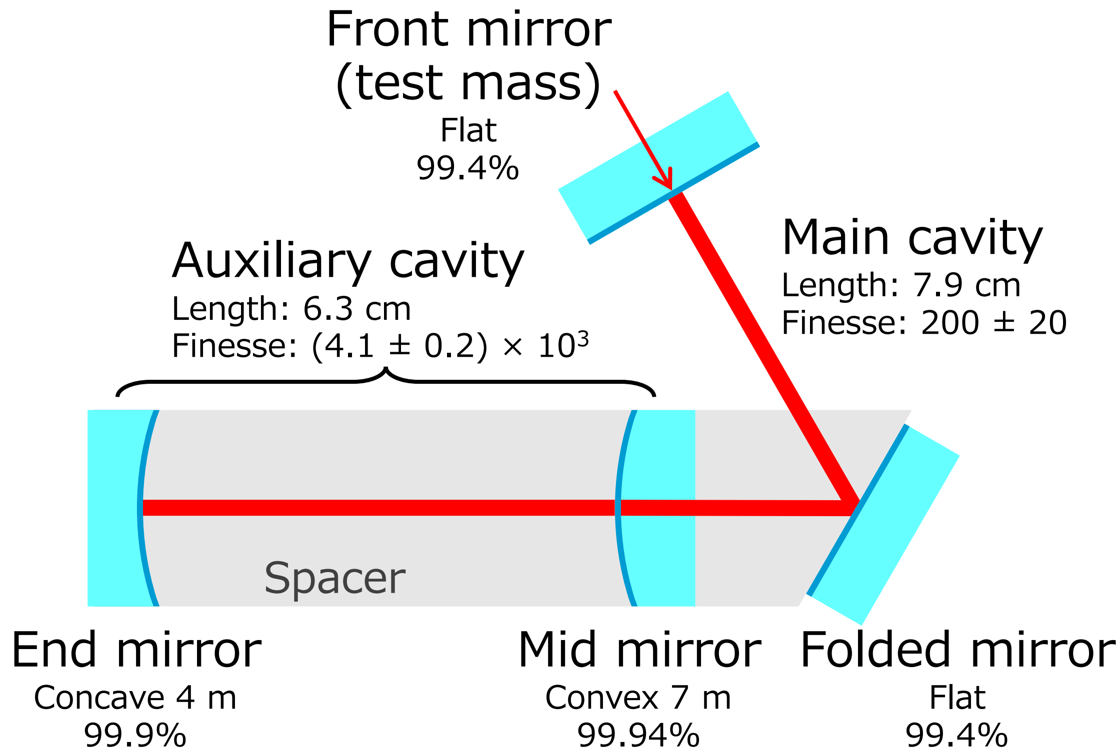
- Evaluate signal amplification
  - Compare the signal intensity of WFS and Coupled WFS
- Establish control method
  - PDH technique for both main and auxiliary cavities

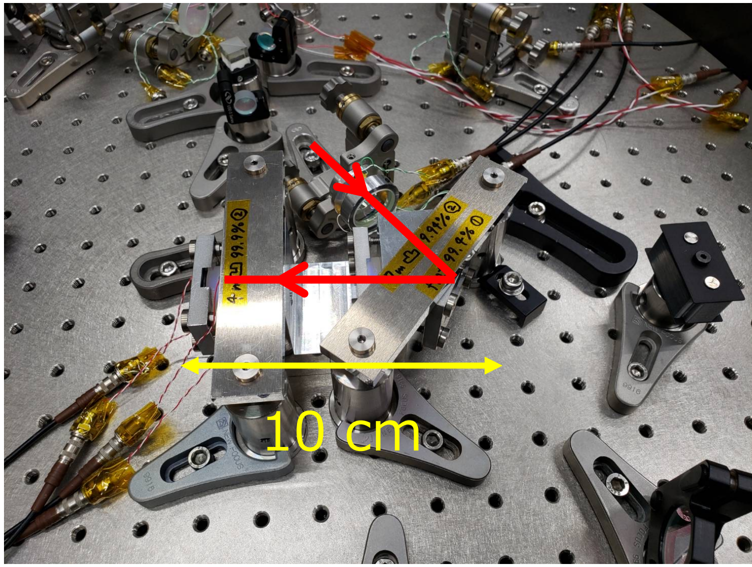




Design of coupled cavity

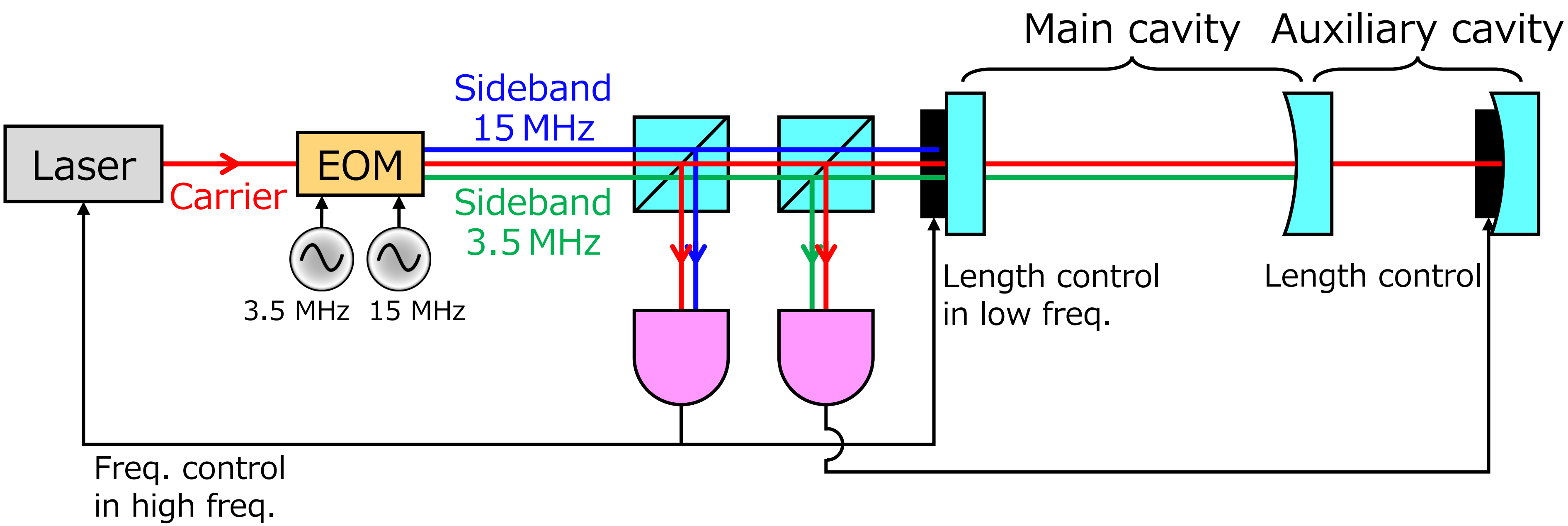
- Parameters are designed to enable phase compensation
  - Reflectivity and loss of the auxiliary cavity are important
    → HR coating is facing the auxiliary cavity
- The main cavity is folded to monitor the transmitted light
- Mirrors are fixed to a spacer to stabilize the alignment





Control method of coupled cavity

- PDH technique with two modulation frequencies
  - 15 MHz for the main cavity
  - 3.5 MHz for the auxiliary cavity
- Hierarchical control for the main cavity
  - To prevent transmitting disturbances
    from the main cavity to the aux. cavity through laser freq.



Results of cavity locking

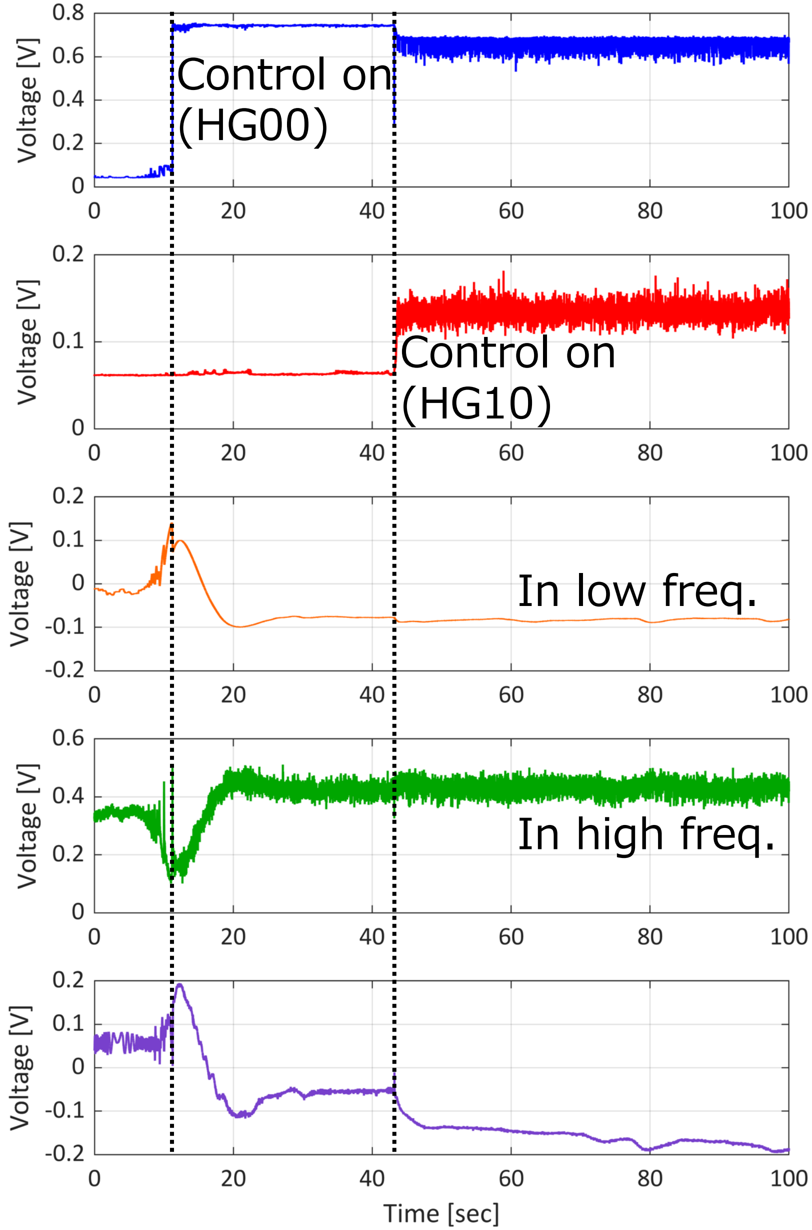
Trans. light of the main cavity

Trans. light of the aux. cavity

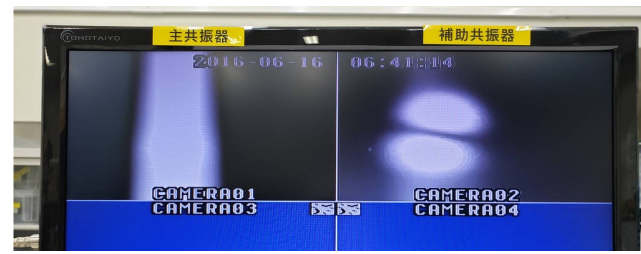
FB signal to the main cavity (front mirror)

FB signal to the main cavity (laser freq.)

FB signal to the aux. cavity (end mirror)



Transmitted light with CCD

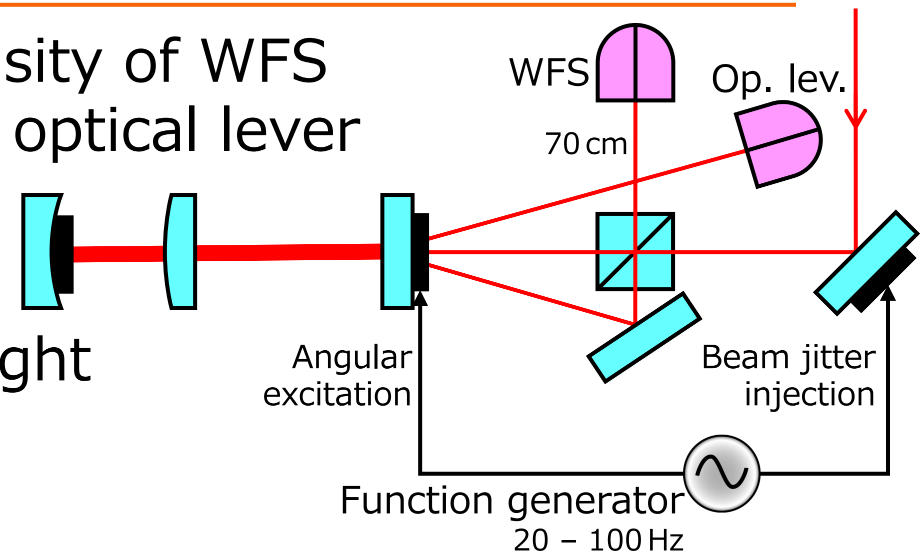


Main (HG00) | Auxiliary (HG10)

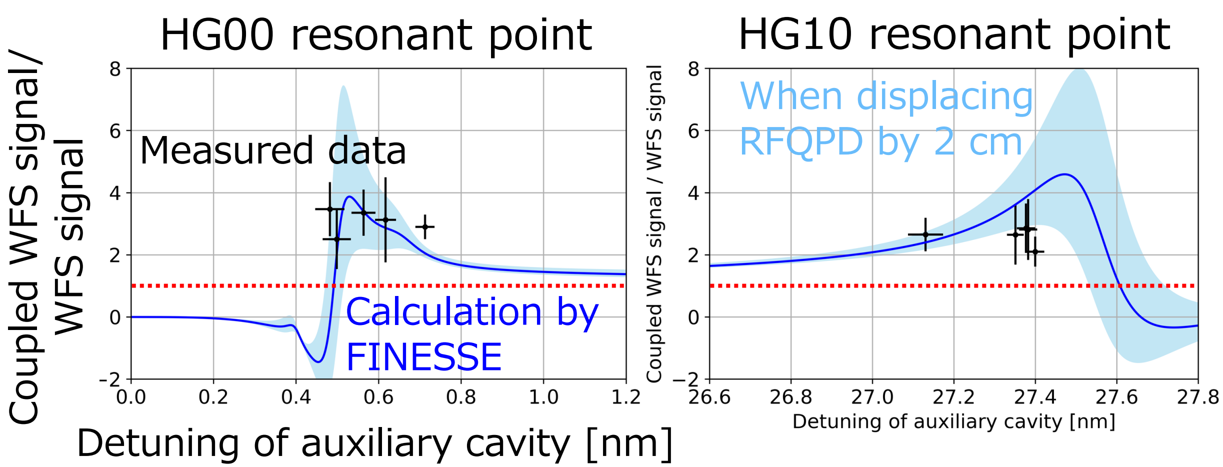
- Cavities were successfully locked to HG00 and HG10 simultaneously

Results of signal amplification

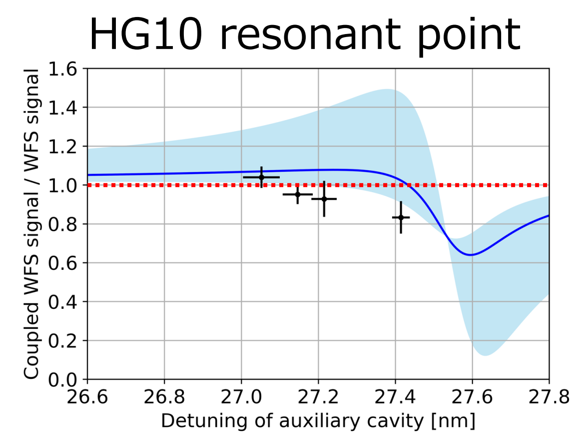
- Calibrated the signal intensity of WFS and Coupled WFS with an optical lever
- Calibrated the lock point of the auxiliary cavity with the power of trans. light



- Angular excitation for front mirror → Signal amplification

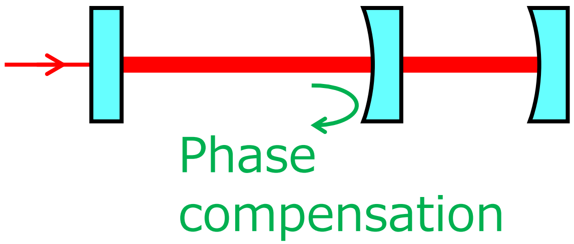


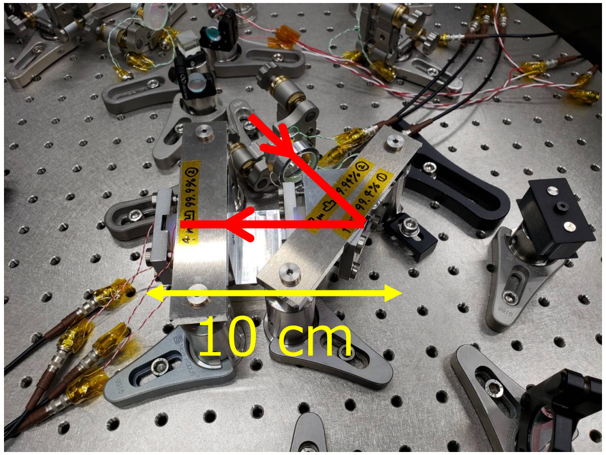
- Beam jitter injection → No amplification



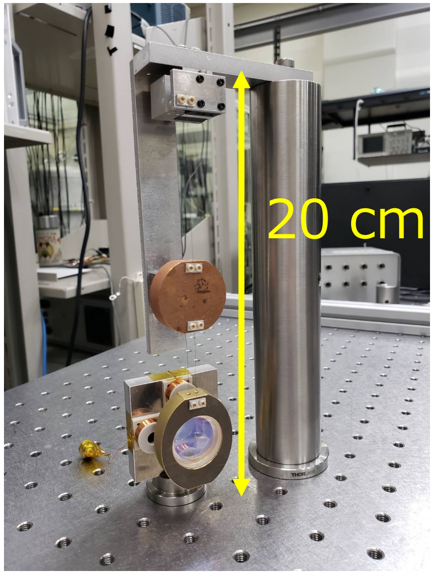
Summary & Future plans

- Developing TOBA to detect GW in low freq.
- Proposed Coupled WFS as an angular sensor for TOBA
- Demonstrated Coupled WFS for TOBA
  - Established control method
  - Evaluated signal amplification





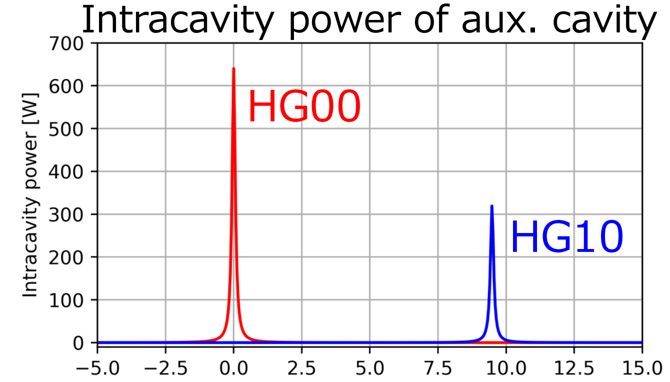
- Plan to suspend the test mass
  to stabilize the cavity lock

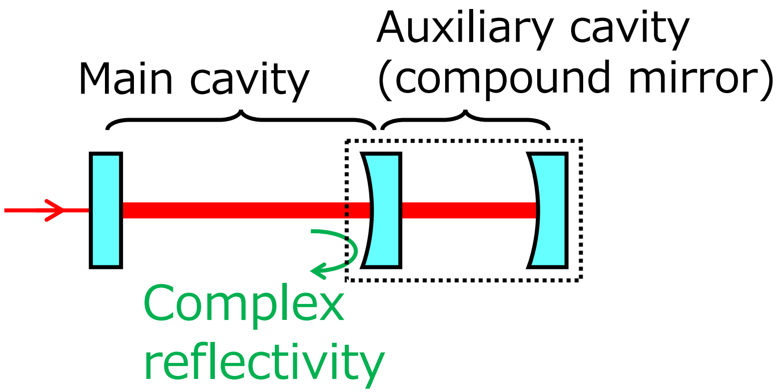


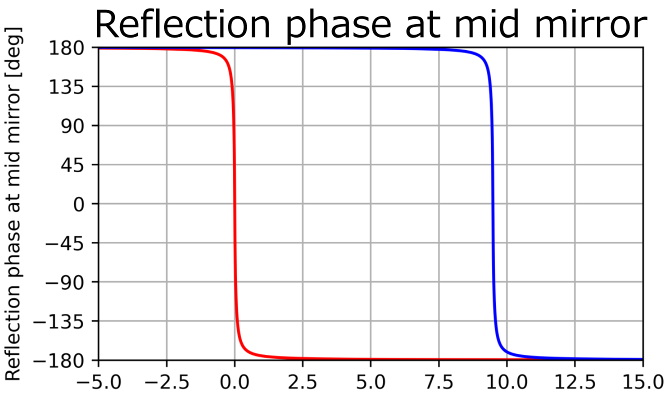
JSR Fellowship This research is supported by JSR Fellowship, the University of Tokyo

Extra slides

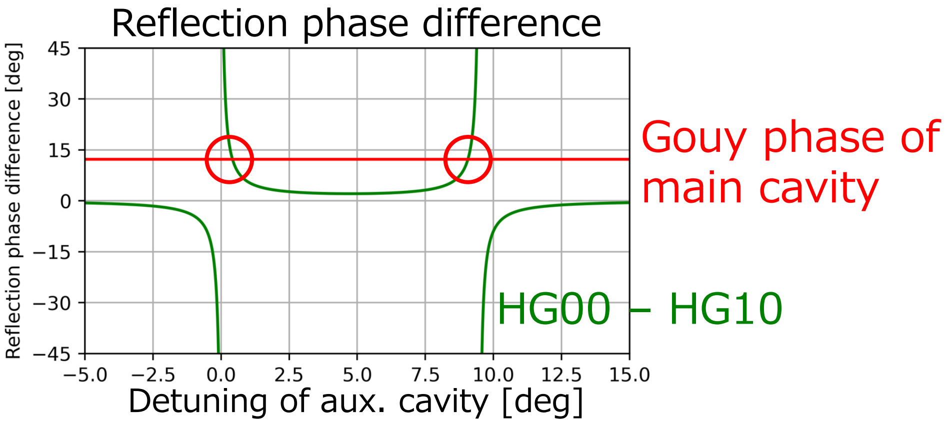
Phase compensation with aux. cavity



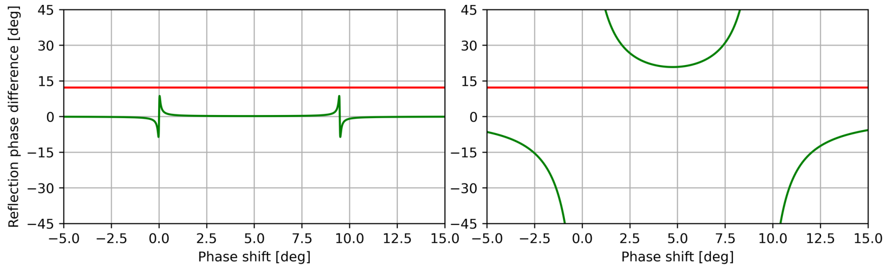




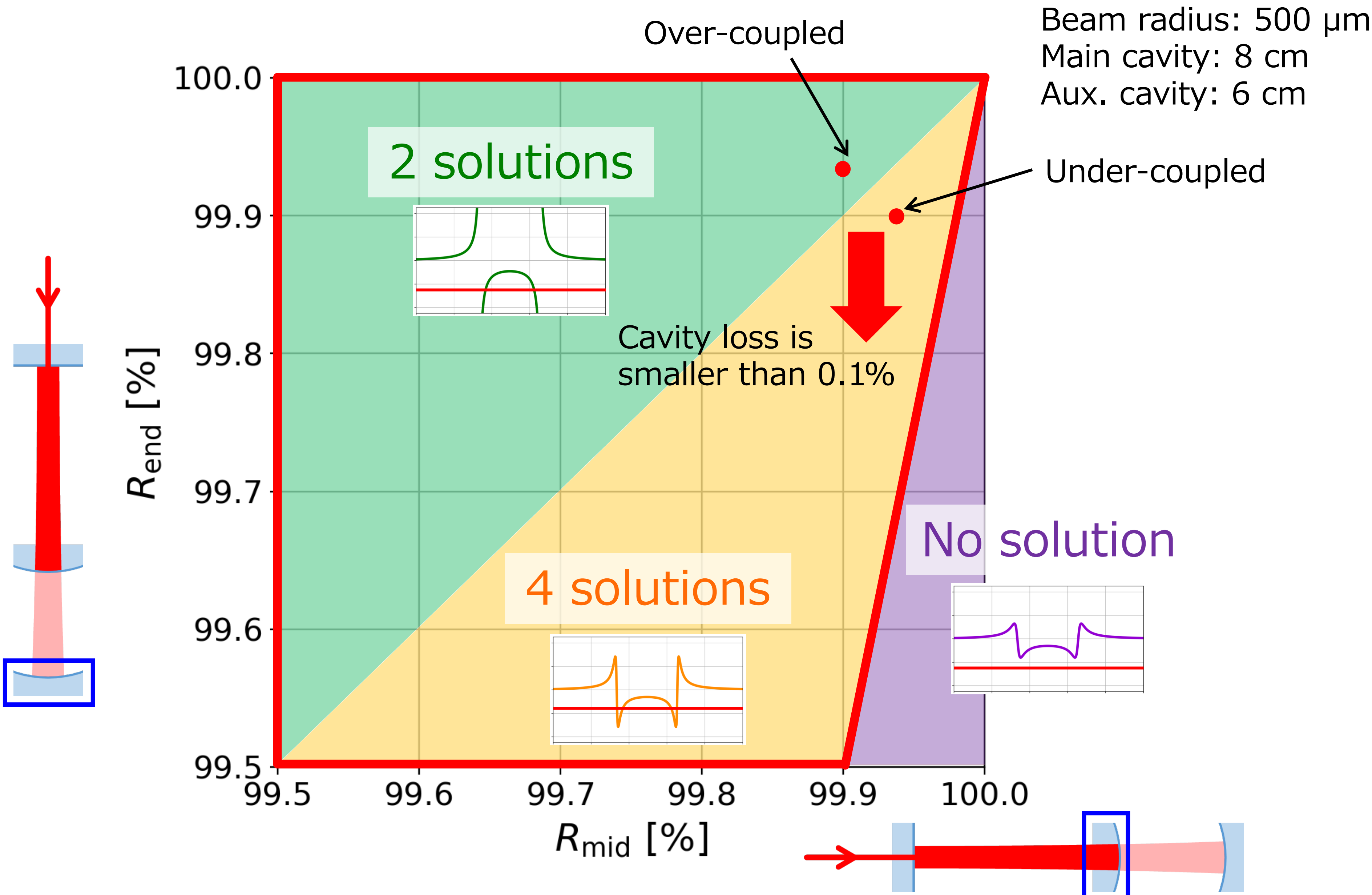
- HG00 and HG10 receive different when reflected at the auxiliary cavity
  → Gouy phase of the main cavity can be canceled



Aux. cavity cannot compensate Gouy phase depending on cavity parameters

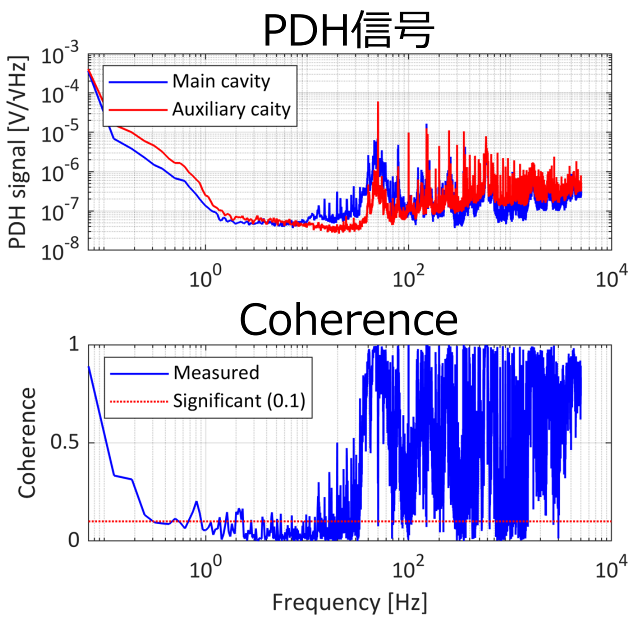


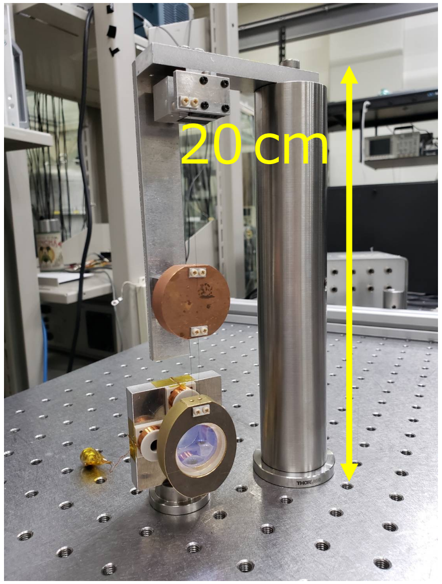
Robustness to cavity loss



Discussion

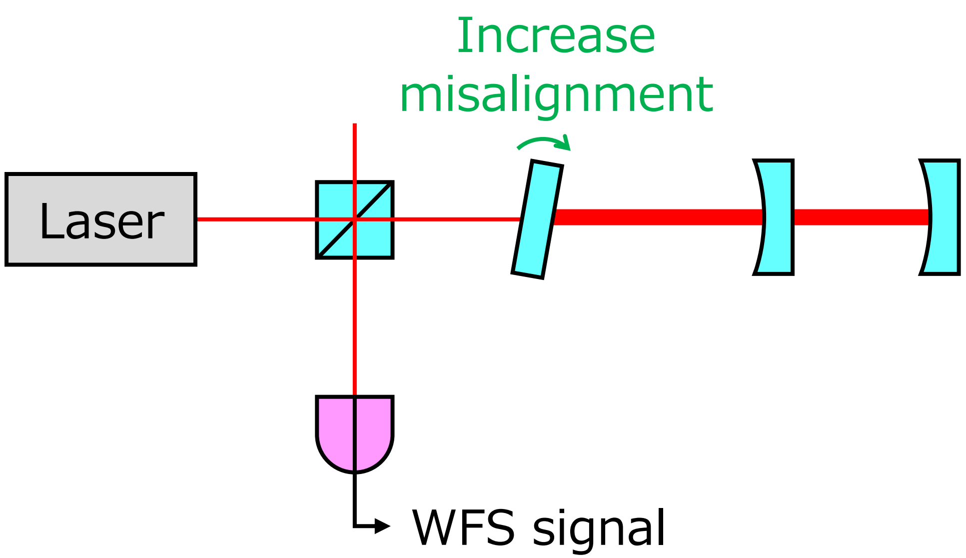
- Current issue
  - High coherence over 40 Hz between two PDH signals
    → FB control is unstable due to narrow-band control
- How to solve
  - Suspend front mirror to reduce disturbance in high freq.
  - Return FB signal to the front mirror
    to reduce the correlation between PDH signals in high freq.

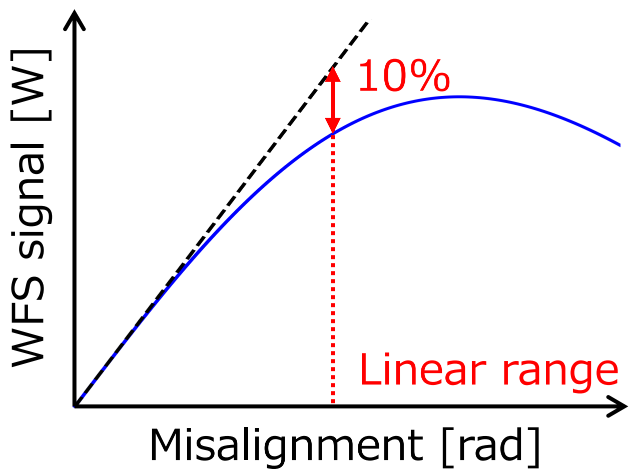




Simulation with FINESSE

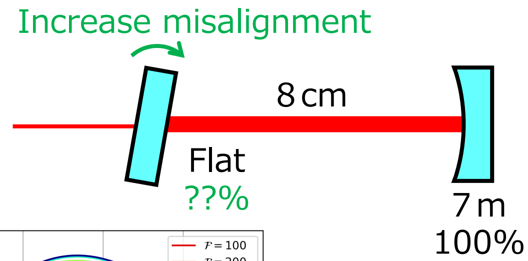
- No analytical solution for linear range
  → Use interferometer simulation software FINESSE
- Calculate Coupled WFS signal with increasing misalignment

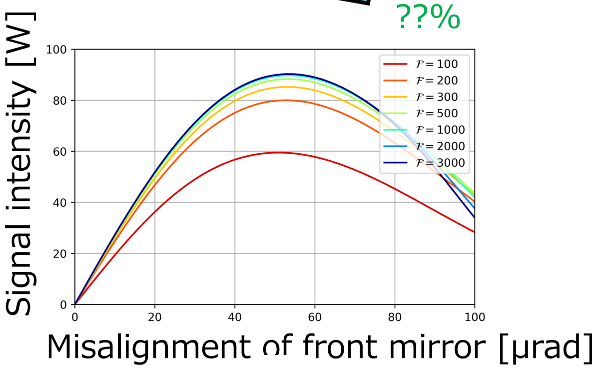


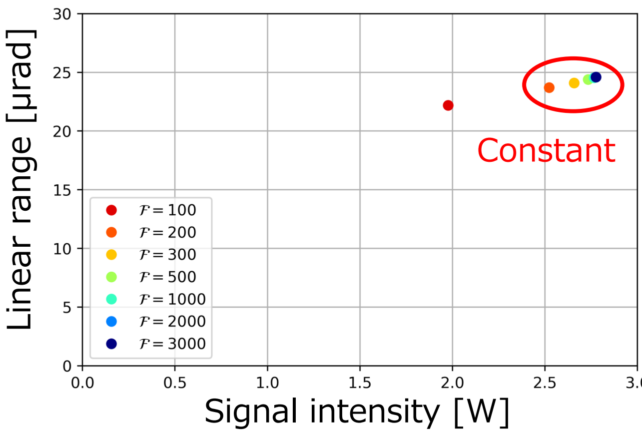


Linear range of Coupled WFS

WFS

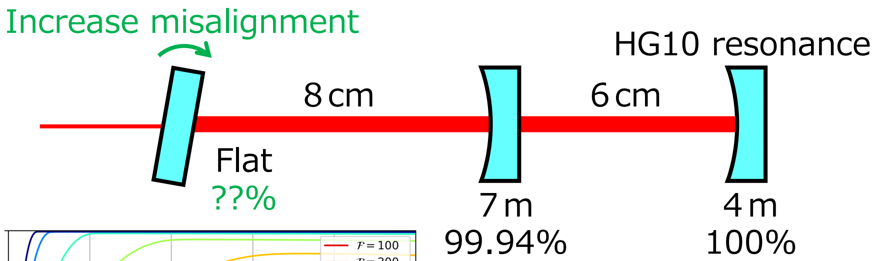


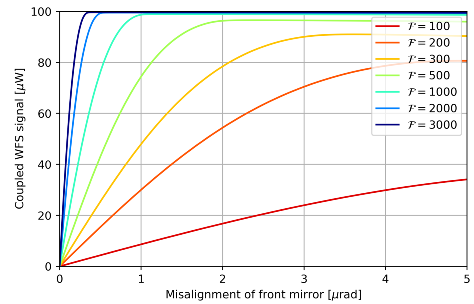


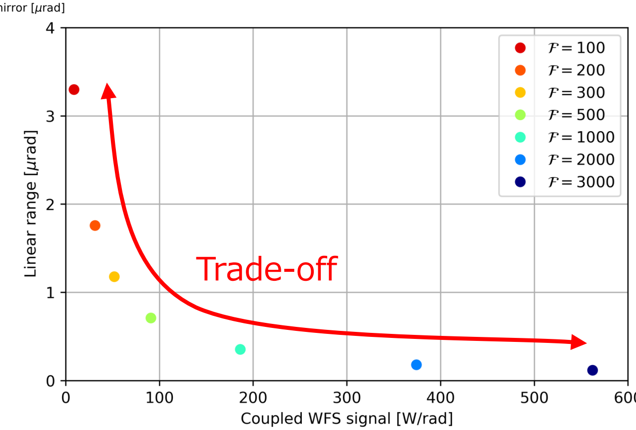


- Signal intensity and linear range are independent of finesse

Coupled WFS



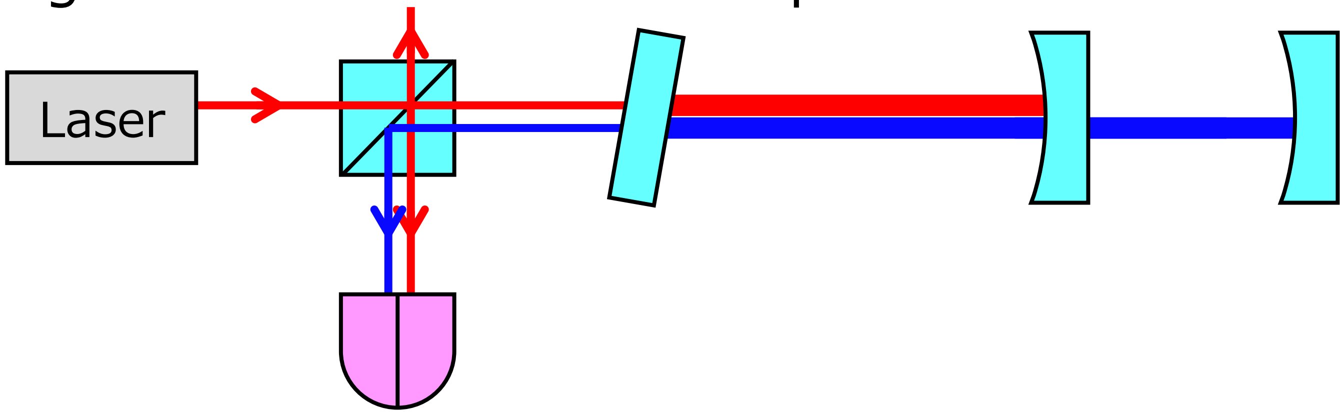




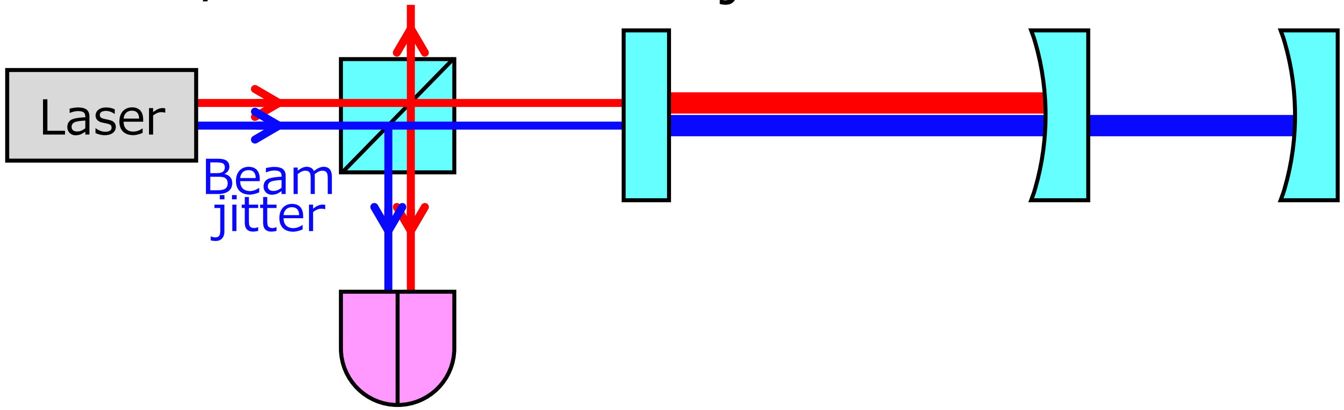
- The larger the finesse, the higher signal intensity, and the smaller the linear range

Beam jitter noise of Coupled WFS

- HG10 generated by mirror tilt is amplified in the cavity and goes out to the reflection port



- HG10 in beam jitter is also resonant in the cavity, but the amount in the incident and reflected light is the same (not amplified)
  → Good S/N ratio for beam jitter noise



Evaluation of cavities

	Quantities	Design values※	Measured values
Main cavity	Finesse	225 – 667	200 ± 20
	Gouy phase [deg]	12.1 – 12.3	12.1 ± 1.0
	Mode-match ratio [%]	–	87 ± 2
Auxiliary cavity	Finesse	$(3.14 - 5.23) \times 10^3$	$(4.1 \pm 0.2) \times 10^3$
	Gouy phase [deg]	9.25 – 9.71	9.54 ± 0.04
	Mode-match ratio [%]	–	94 ± 2

※ Calculated from Layertec spec values

- Measured finesse of aux. cavity is consistent with design
- Measured Gouy phase is consistent with design
  → Phase compensation is possible
- Measured finesse of main cavity is smaller than design
  → Loss in AR coating is the cause
- Mode match ratio is large enough